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"Adaptive Optics Imaging of Solar System Objects"

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Submitted by

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1996 PROGRESS REPORT

GRANT TITLE: Adaptive Optics Imaging of Solar System Objects
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INSTITUTION: Institute for Astronomy (IfA), University of Hawaii.

ABSTRACT

Goals:
Because space probes such as Voyager were not equipped to observe in the infrared, most solar system objects have never been observed at wavelengths longer than the R band with an angular resolution better than 1". The Hubble Space Telescope itself is not yet equipped to observe in the infrared. When it is, its resolution will still be limited by its aperture size. We propose to use adaptive optics (AO) on 2 to 4-m class telescopes to obtain diffraction-limited images of solar system objects at far red and near-infrared wavelengths (0.7–2.5 μm) which best discriminate spectral signatures, for a variety of possible surface or atmospheric compositions. Our efforts will be put into areas of research for which high angular resolution is essential, such as the mapping of Titan and of large asteroids, the composition of Neptune clouds, and the infrared photometry of satellites previously undetected from the ground such as Proteus.

Progress and Accomplishments:
High angular resolution images of Saturn's ring system were obtained as the Earth – and later the Sun – were crossing the ring plane. Most of Saturn's faint satellites were observed as well as 12 new objects, including two detected by the Hubble Space Telescope. Astrometric, and photometric analysis of these images is still in progress. High angular resolution images of Titan were obtained in the J and H bands. Evidence was found for a bright continental-size feature in the leading hemisphere, whereas the center of the trailing hemisphere was found to be dark. The south hemisphere appears systematically brighter, owing to a stronger scattering of the light by the atmosphere. We confirmed that below 30° latitude, Neptune's atmospheric activity moved since Voyager from the South to the North hemisphere, and we have detected Proteus (largest of the dark satellites of Neptune) and made the first measurement of its albedo in the K band. We have also successfully mapped Vesta in the pyroxene band confirming the existence of a nearly intact basaltic crust with a few fresher regions corresponding to impact craters or lava flows.

Anticipated Accomplishments:
• *Mapping of Titan*. We will reduce narrow-band data recently obtained on the leading hemisphere, and attempt narrow-band observations of the trailing hemisphere to constrain the surface composition, particularly the dark patch. We will also search for clouds that have significant infrared contrast in the wings of the strong methane bands.
• *Individual photometry of Pluto and Charon*. We plan to observe and compare Pluto and Charon through narrow band filters which will isolate the H_2O ice absorption at 1.55 μm, the continuum at 1.33 μm, and the H_2O absorption at 2.0 μm, as well as filters designed to isolate the absorption features of methane. Due to the 6.4-day rotation, nightly observations provide data with approximately 60 degree longitudinal spacing.
• *Observations of Neptune*. We plan to observe the clouds through the same set of filters used for Pluto-Charon. These observations should allow us to distinguish among three possible cloud compositions: methane ice, water ice (from comets), and a neutral scatterer such as crystals of argon, nitrogen, or dust. J, H, and K band photometry of Proteus will be a first step toward constraining models for its surface composition. A deep integration through a K' filter (to reduce both the scattered light from Neptune and the thermal background) may produce the first ground-based image of the rings, allowing us to examine the current configuration of the "arcs".
• *Surface mapping of Ceres and Vesta*. We plan to image Ceres inside and outside the water ice absorption bands located at 1.5 and 2 μm to measure the distribution of hydration over its surface as well as to search for polar caps and attempt to measure their latitudinal extension. We also plan to complete our mapping of Vesta through narrow-band filters in the [0.9 - 2.3] μm region to measure the spatial distribution of pyroxene, feldspar and olivine.

Relevant Publications

Brahic, A., Dumas, C., Ferrari, C., Graves, J. E., Han B., Northcott, M., O'Connor, D., Owen, T., Perret, L., Roddier, C., Roddier, F., Thébault, P., "Saturn's rings edge-on observations at 0".1 resolution with adaptive optics," D.P.S. meeting, Bull. Am. Astr. Soc. **27**, p. 1132, 1995.

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F. Roddier, A. Brahic, C. Dumas, C. Ferrari, J. E. Graves, M. J. Northcott, T. Owen, L. Perret, C. Roddier, and P. Thebault, "Satellites of Saturn," IAU Circular No. 6407, 1996.

C. Roddier, F. Roddier, A. Brahic, J. E. Graves, M. J. Northcott, T. Owen, "Satellites of Saturn," IAU Circular No 6515, 1996.

F. Roddier, C. Roddier, A. Brahic, C. Dumas, J. E. Graves, M. J. Northcott, T. Owen, "First Ground-Based Adaptive Optics Observations of Neptune and Proteus," submitted to Planetary & Space Science, 1996

C. Roddier, F. Roddier, A. Brahic, C. Dumas, J. E. Graves, M. J. Northcott, T. Owen, "Adaptive optics observations of Saturn's ring plane crossing by the Earth at the CFHT," (in preparation)

Conrath, B. J., Gautier, T. C., Owen, T. C., and Samuelson, R.E., "Constraints on N2 in Neptune's Atmosphere from Voyager Measurements," Icarus, **101**, pp. 168-171, 1993.

Barucci, A., Lazarrini, M., Owen, T., Barbieri, C. and Fulchignoni, M.: "Near infrared spectroscopy of dark asteroids," Icarus **110**, pp. 287-291, 1994.

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PROGRESS and ACCOMPLISHMENTS

Adaptive optics (AO) systems are now being routinely used both at the 3.6-m Canada-France-Hawaii Telescope (CFHT) and at the Mount Wilson Observatory, producing diffraction-limited images down to the visible. We give here a progress report on the results obtained to date at the Institute for Astronomy (IfA) in the field of planetary sciences. Most of the results reported here are from observations made in August and November 95 with the main purpose of observing the rings of Saturn during the crossing of the ring plane by both the Earth and the Sun. Additional observations of Titan, Neptune, and asteroids were made in June-July 1996 and in November 1996. These data have only partly been reduced. Future planned observations and anticipated accomplishments are described in a following section.

1. Saturn ring-plane crossing

Bright satellites such as Dione and Tethys were used as natural guide stars to record high angular resolution images of the Saturn ring system. Data taken in August span over 4 nights (Aug. 9-12) as Earth was crossing the ring plane. Several hundred exposures 15-, 30-, and 60-s long were obtained each night in the J, H, and K infrared bands. Average resolution is 0".15 in the H band. Data reduction is now nearing completion and a paper is in preparation. All known faint satellites have been detected and identified except Atlas. These are: Saturn X (Janus), XI (Epimetheus), XII (Helene), XIII (Telesto), XIV (Calypso), XV (Pandora), and XVI (Prometheus). Positions are in fair agreement with the new ephemerides deduced from Hubble Space Telescope (HST), although minor discrepancies remain. In addition, 12 new objects were found to orbit Saturn all in the F ring at approximately the same distance from Saturn (Fig. 1). Estimated radii range from 10 to 20 km. A good orbital fit (including the effects of Saturnian J2 and J4 harmonics) was obtained for all of them with a single distance of 140.500 km +/- 500 km. Two of these objects have their estimated orbit consistent with objects S5 and S7 detected by HST. Our observations of 12 objects cover a total longitude range of 135 deg. Assuming that these objects are uniformly distributed along the F ring, one can estimate that the F ring contains about 32 objects with a radius larger than 10 km (IAU Circulars No. 6407 and 6515). A detailed photometric analysis of the ring system and the satellites as they evolve with time is now in progress (Fig. 2). This work is done in cooperation with André Brahic and his coworkers (Observatoire de Paris, France).

2. Titan

We have observed Titan in December 1994, August 1995, November 1995, and November 1996. The opacity of Titan in the near-infrared is dominated by methane absorption. There are, however, several "windows" in the absorption near 1.3, 1.6, and 2.0 μm which can readily be observed with J, H, and K broad-band filters. Our data set currently consists of images of Titan taken in the H and K bands, near both the eastern elongation, and the western elongation. After background subtraction and flat-fielding, images have been deconvolved using a psf standard star.

a) *Eastern elongation.* Fig. 3 shows an image of Titan taken in K-band near greatest eastern elongation with a Longitude of Central Meridian (LMC) of 105°. This image was taken from a set of observations made in December 1994. North is up and East is left. Note the presence of the bright patch near the equator/southern hemisphere. Its longitude corresponds well to that of the bright spot seen in the HST images of Smith et al. It is seen on successive nights as well as on images obtained independently with different deconvolution algorithms, and is therefore believed to be real. In order to remove atmospheric effects, a disk profile has been fitted to the data with the bright spot masked out. This disk profile has then been subtracted to yield the above image.

b) *Western elongation.* Fig. 4 shows an image of Titan taken in K-band near greatest western elongation with an LMC of 280°. This image is taken from a set of observations made in

August 1995. North is up and East is left. The dark spot near the equator is a feature seen on two consecutive nights with an approximately 7% decrease in flux from a profile fitted to the data with the spot masked out (this fit has not been subtracted here). There is a significant north-south hemispheric asymmetry in this image, reminiscent of the asymmetry seen by Voyager.

During the November 1996 run, we observed the leading hemisphere of Titan over several days in order to corroborate features (Titan rotates approximately 22° per night). Observations were made both through broad-band (J, H, and K) as well as narrow-band filters centered on the wings of the methane absorptions. With spatially resolved three-color images, we will be able to begin constraining the composition of the surface as a whole and the bright patch in particular. The narrow-band data will be useful to enhance contrast and to search for methane clouds that have significant infrared absorption in the wings of the methane absorption windows.

3. Uranus and Neptune

During the August run a few snapshots were taken on Uranus and Neptune in the K band. Satellites such as Ariel, Titania, or Oberon are bright enough to be used as guide sources for Uranus, whereas Triton can be used to image Neptune. Because of the methane absorption bands, the Uranus image is quite dark. Apart from a slight limb brightening, it shows no surface feature. In this wave-band, the ring is brighter than the planet, and clearly asymmetric. Images show Puck a satellite discovered by Voyager. We have detected it for the first time in the K-band.

The K-band images of Neptune (Fig. 5) show bright high contrast features that are believed to be high altitude clouds. They confirm that low latitude (< 30°) cloud activity has shifted since Voyager from the south hemisphere to the north hemisphere, whereas higher latitude activity seems more permanent. Proteus can be seen at the exact location predicted from Voyager data. This is the first ground-based detection of one of the dark satellites of Neptune discovered by Voyager. We have estimated its K-magnitude to be 19.0 ± 0.03. The corresponding geometrical albedo is identical to that measured in the visible by Voyager. A paper on Neptune has been submitted to Planetary & Space Science.

4. Pluto and Charon

We have already obtained a few wide band images of Pluto and Charon using the object itself as a guide source. In all cases, the two components are well resolved. It gives us confidence that a program of narrow-band photometry of the individual components can be successfully attempted.

5. Asteroids

This year, we obtained narrow-band, diffraction-limited images of the asteroid Vesta using several adaptive optics systems both in the visible and near-infrared. These spectral regions contain the signature of most of the minerals present on their surface. Vesta is one of the most fascinating among the asteroid main belt population. Indeed, Vesta is the only large differentiated asteroid that hasn't been broken into small fragments during impacts with other main belt bodies. By looking at this asteroid, we will better understand the early processes that led to the formation of the terrestrial planets by accumulation of smaller differentiated bodies similar to Vesta.

The 1996 opposition of Vesta offered an excellent geometry with more than 99% of its surface visible during a rotation period. Its 1996 angular diameter (0.65 arcsec) was above the mean opposition-diameter of Vesta (0.45 arcsec) allowing about 30 resolution elements to map its surface. The prospects were to image Vesta across the absorption bands of the pyroxene, feldspar and olivine in order to measure their surface distribution.

Early June, we obtained images of Vesta with the new AO system Pueo at the Canada-France-Hawaii Telescope (CFHT) while the asteroid was very close to opposition. The images recorded through a narrow band filter centered at 2.02 μm (bottom of the pyroxene band), show a dramatic feature on one hemisphere.

Other CFHT observations were scheduled early July using the IfA AO system. The aim was to map Vesta both in the visible using a camera CCD and in the near-infrared with the QUIRC camera. Unfortunately, technical problems with QUIRC prevented us to image Vesta using the narrow band filters ordered for this observing run. Only CCD images through a narrow band filter centered at the bottom of the pyroxene band were recorded. Moreover, bad weather conditions prevented to obtain the complete coverage of Vesta at this wavelength.

Visible CCD images were also recorded early June at Mount-Wilson Observatory using the new adaptive optics system mounted on the 100 inch telescope (Fig. 6). We were able to image the entire surface of Vesta by scanning the first pyroxene band through three narrow-band filters between 0.70 μm to 0.93 μm. This data set confirm the spectrophotometric results obtained by Gaffey (1996 - to be published in Icarus) suspecting a nearly intact basaltic crust with a few fresher regions corresponding to impact craters or lava flows. Our images provide an absolute determination of the location of these features. Without the near-infrared data, their nature cannot be absolutely determined but we can certainly discriminate the eucritic rich regions (oldest) from the diogenite or olivine regions which correspond to fresher material excavated from below the crust. These images show also that the shape of Vesta is very irregular and that its south pole depart from an hydrostatic equilibrium shape. This data set is actually being reduced and analyzed and a paper summarizing the ground-based results obtained during the two last oppositions of Vesta will be submitted early 1997.

Publications

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C. Roddier, F. Roddier, A. Brahic, J. E. Graves, M. J. Northcott, T. Owen, "Satellites of Saturn," IAU Circular No. 6515, 1996.

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C. Roddier, F. Roddier, A. Brahic, C. Dumas, J. E. Graves, M. J. Northcott, T. Owen, "Adaptive optics observations of Saturn's ring plane crossing by the Earth at the CFHT," (in preparation)

Dumas, C., O. R. Hainaut et al. "Ground-Based High Resolution Imaging of 4 Vesta: the 1994 and 1996 Oppositions" (in preparation)

Dumas, C., T. Owen, A. Barucci "Near-Infrared Spectroscopic Survey of Low Albedo Asteroids: A Search for Organics"(in preparation)

ANTICIPATED ACCOMPLISHMENTS

Two nights have already been allocated for this program, with the IfA AO system mounted at the CFHT f/35 focus. The period (July 15-16, 1997) is close to the opposition of Pallas. The 13-actuator IfA AO system is currently being upgraded to a 36-actuator system and should be ready by then.

1. Titan

Next year, we will concentrate on Titan's trailing hemisphere and build a spatially-resolved three color map to better constrain the nature of the dark patch. All of these data and analyses are necessary precursors to the *in situ* measurements that Cassini-Huygens will make in the early part of the next century.

These observations are part of the dissertation subject of Byron Han, under supervision by Toby Owen. Data will be taken and reduced by Byron Han.

2. Pluto and Charon

Because Pluto and Charon are always less than 0.9" apart, most compositional observations of Pluto and Charon have been made with combined light of the two bodies. Only in 1987 and 1988, when Charon was hidden behind Pluto, could data be obtained on the individual bodies. The surface of Pluto was found to be covered by a mixed deposit of ices of N_2, CO, and CH_4, with no evidence of H_2O (Owen et al. 1993), while the surface of Charon appears to be covered with H_2O ice, but no other species have been confirmed (Buie et al. 1987, Fink & Desanti 1987, Marcialis et al. 1987)). If this is true, it is a major constraint on models for the origin and evolution of this system. However, these results are not definitive (Roush 1995). Because of the tidal locking between Pluto and Charon, only one hemisphere of each body was represented. Yet the brightness of the whole system varies by 0.3 mag over one rotation, indicating albedo variations with an amplitude second only to Iapetus in the Solar System. An irregular distribution of methane frost over the surface of Pluto may be responsible (Buie & Fink 1987).

Adaptive optics allows us to improve this situation. We will use narrow band filters to isolate the H_2O ice absorption at 1.55 μm, the continuum at 1.33 μm, and the H_2O absorption at 2.0 μm. A comparison of Pluto and Charon at these wavelengths will tell us just how different the two surfaces are. Europa (JII) will be used as our calibration for ice. We will also look for other ice species, which have absorption features in the near infrared, using filters designed to isolate the absorption features of methane, water, and continuum. Due to the 6.4-day rotation, nightly observations provide data with approximately 60 degree longitudinal spacing.

Data on this object will be taken in July, and reduced by Dave Tholen. Both Toby Owen and Dave Tholen will work on the interpretation.

3. Neptune

The following observations will be attempted:

1) *Narrow band photometry of the clouds.* It is commonly assumed that the clouds are composed of condensed methane, but there is no proof of this. We plan to observe the clouds through the same set of filters used for Pluto-Charon. These observations should allow us to distinguish among three possible cloud compositions: methane ice, water ice (from comets), and a neutral scatterer such as crystals of argon or nitrogen, or dust. Additional importance is given to this study by the current difficulty in determining the nature of the clouds on Jupiter from the Galileo probe data.

2) *Wide band photometry of Proteus.* Our successful detection of Proteus give us an opportunity to attempt a J, H, and K band photometry of this object as a first step toward constraining models for the surface composition. There is now a wealth of colorimetric data on the dark objects in the outer solar system. The goal is to see what relationships exist among these various objects that could provide clues to their origin.

3) *Detection of Neptune rings.* They have not yet been seen from the Earth. The discovery of three discrete condensations in the outer or Adams ring of Neptune was one of Voyager's most surprising findings. There is not yet any good theoretical understanding of how these condensations form or what keeps them in place. A first order question concerns their stability. How long can they survive in their present configuration? We can begin to answer this question as soon as we are able to detect them. To achieve this goal, we plan to make a deep integration through a K' filter, to reduce both the scattered light from Neptune and the thermal background. If this is successful, we will supplement it with a second integration at shorter wavelengths, to obtain some colorimetric information.

Data on Neptune will be taken and reduced by C. Roddier, who has already a good experience in working with adaptive optics data. Interpretation will be done in collaboration with Toby Owen and André Brahic's group (Observatoire de Paris, France).

4. Asteroids

As we have demonstrated, adaptive optics is a powerful mean to map surface features on the largest asteroids. High angular resolution imaging in the visible and near-infrared provides sensitivity to most of the minerals present on their surface. In the forthcoming runs we plan to complete our mapping of Vesta and to image for the first time the surface of Ceres and Pallas in/out the bands of water ice.

Our recent results show that Vesta has received relatively few major impacts since its formation. Its surface is quite similar to the Moon's surface, with some regions dating from the time when the whole body was still cooling down (basaltic crust) while some others display fresher material excavated by impactors or due to lava flows reaching the surface through cracks. The near-infrared images that we are planning to obtain next year will permit an absolute discrimination between olivine, feldspar and pyroxene. The determination of the mineralogical nature of the features visible on Vesta will bring some important constraints to understand the formation of Vesta and its differentiation. Indeed, olivine is expected to come from the deep interior while the pyroxene regions might correspond - depending the level of differentiation - either to some regions where the crust has been removed by a crater impact to show part of the mantle - or to some surface patches created during the cooling of Vesta material.

Unlike Vesta, previous observations of Ceres and Pallas showed that their surface has been highly altered by impact cratering with smaller objects during their lifetime. These events have redistributed the material over the whole surface, wiping off any record of the physical processes undergone earlier by these asteroids. But theoretical calculations (Fanale et al., 1989) and spectroscopic measurements (Lebofsky et al., 1981) have shown that boundary water might be present on the surface of Ceres and Pallas. Because Ceres is large enough to sustain an important quantity of boundary water, some permanent polar caps might also be present. We will image Ceres and Pallas inside and outside the water ice absorption bands located at 1.5 and 2 μm to measure the distribution of boundary water over their surface as well as to search for polar caps on Ceres.

These observations will lead to a better understanding of the physical processes that occurred during and after the formation of the planetesimals, and will enlarge our knowledge of the regolith chemistry of the minor planet surfaces. They are part of the dissertation subject of Christophe Dumas, under supervision by Toby Owen. Data will be taken, reduced and interpreted by C. Dumas, and O. Hainaut, in collaboration with T. Owen.

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BUDGET

Support for the first year was insufficient to cover a full time post-doc salary. We therefore decided to distribute the heavy data reduction load between IfA staff members (C. Roddier, F. Roddier) and graduate students (C. Dumas, B. Han). Part of the grant has been used to cover the observational expenses (travel and stay for two runs on Mauna Kea), as well as computer charges. Another part has been used to support an assistant specialist who has upgraded the IfA instrument, as made necessary by these observations (e.g.: addition of a new filter wheel, detector upgrade). New detectors have been purchased on an NSF grant. They will allow us to guide directly on Neptune or Uranus with enhanced compensation performance. We are also upgrading the current 13-actuator IfA AO system into a 36-actuator system. To continue this work, a similar level of support is necessary for the second year, for the same purpose.

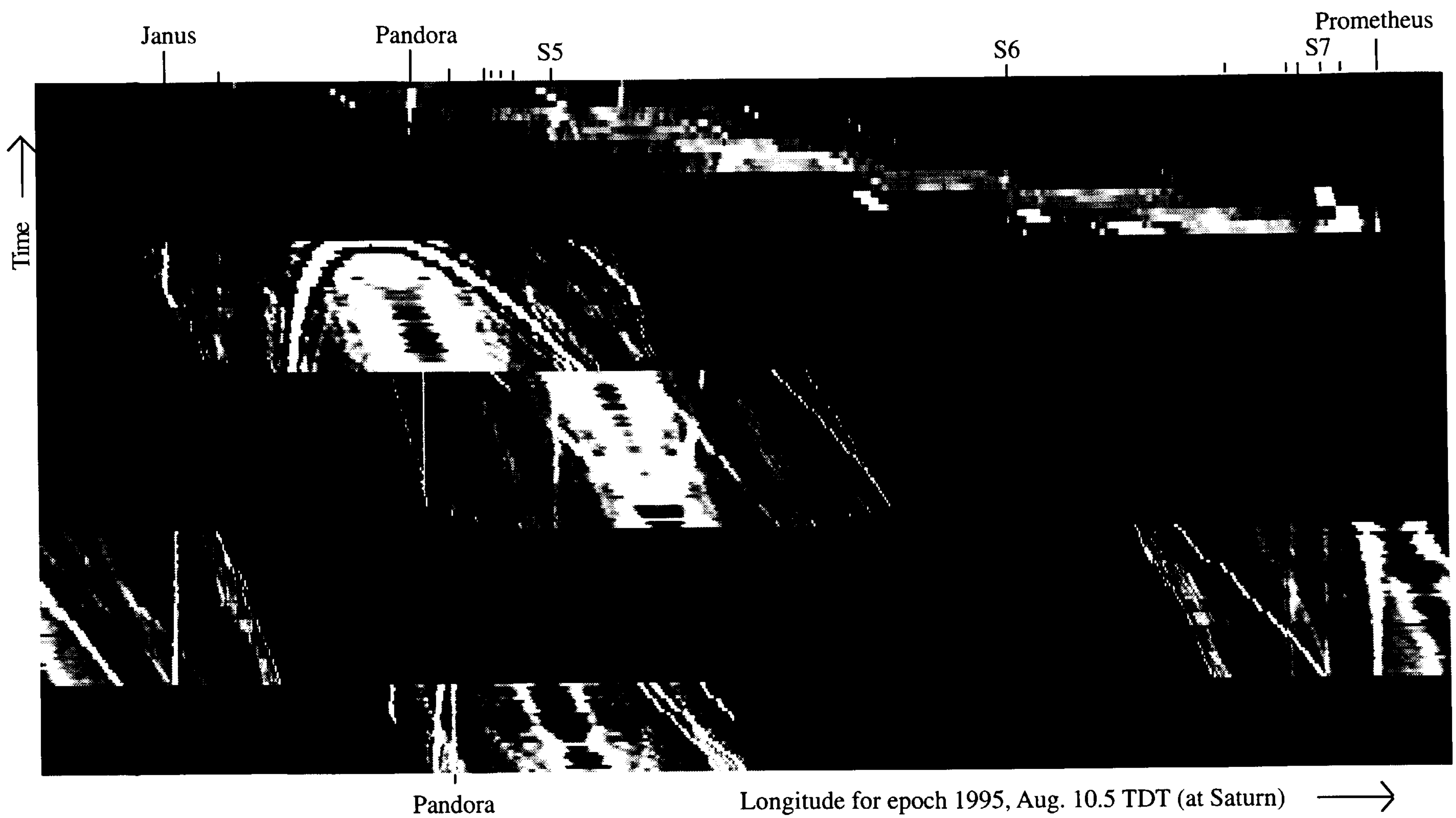

Fig. 1. *From bottom to top*: time sequences of the illumination in the Saturn ring system. The four large horizontal bands are CFHT adaptive optics results obtained around the central decimal dates of Aug. 9.62, 10.48, 10.52, and 10.62 (UT). The narrower bands at the top are the HST results obtained near the crossing time (Aug. 10.87). The illumination is displayed as a function of longitude assuming a Keplerian rotation at a distance of 140,500 km from the center of Saturn (in the F ring). In this representation, any object rotating at this distance will appear as a bright vertical line. Objects orbiting at a different distance will appear as inclined or bended lines. Note the large number of faint objects orbiting at the selected distance (small ticks on top). The brightest can be seen in the HST data as well, whereas the faintest were blurred by the long HST exposure time (100 sec). S5, S6, and S7 are the three objects announced by the HST team. See IAU circulars No. 6243, 6407, and 6515.

Pandora Epimetheus

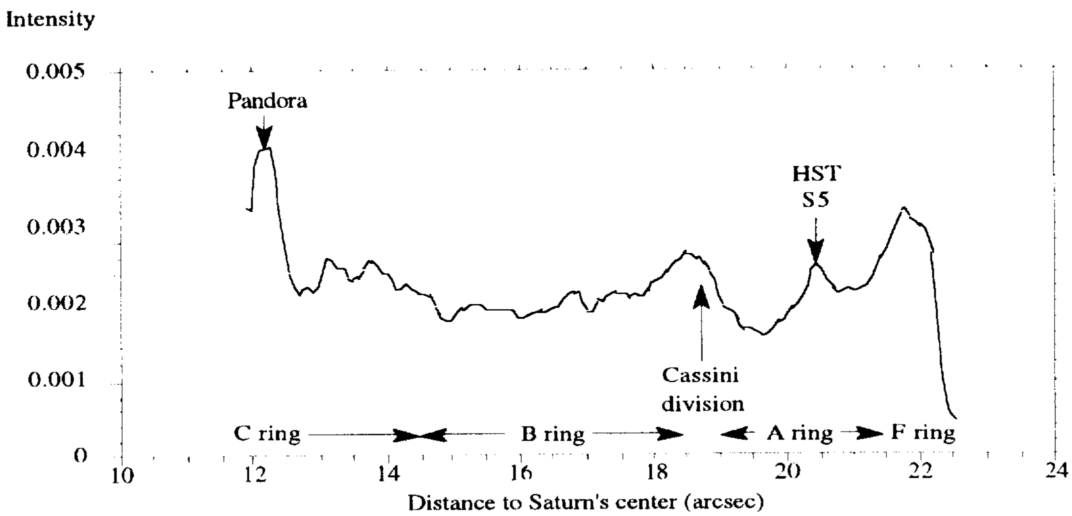

Fig. 2. Saturn's ring image (top) and intensity profile (bottom) observed on Aug 10.5 (UT) about 8 hours before the crossing. One still see the dark side of the rings. Bright regions correspond to the C ring, the Cassini division and the F ring. Epimetheus has been removed from the profile. Object S5 observed by the Hubble Space Telescope is clearly seen here.

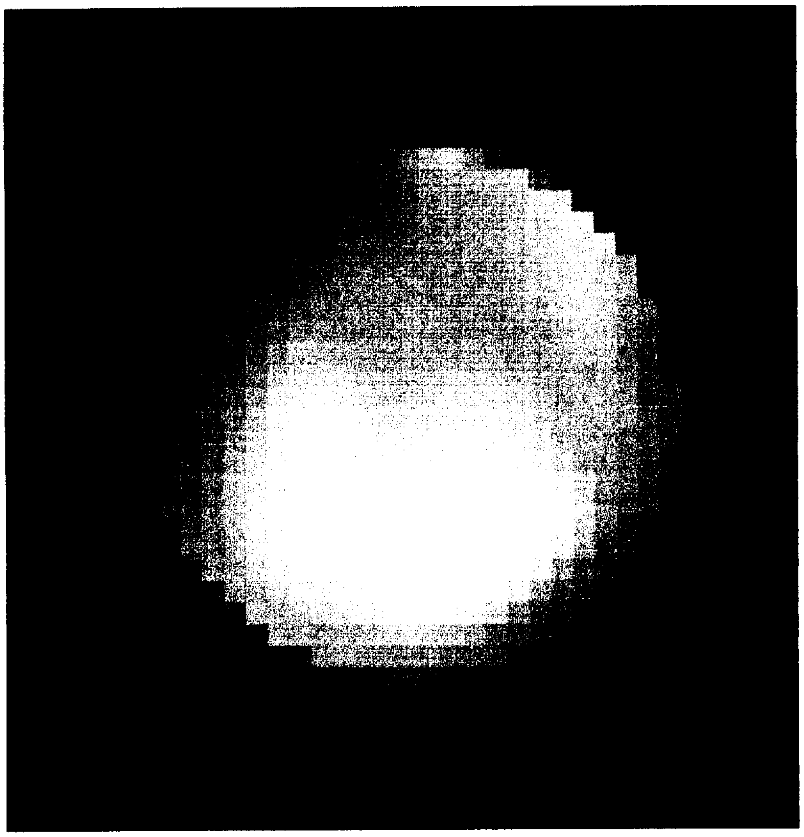

Fig. 3. Titan K-band image taken near eastern elongation (LMC of 105°). This image is taken from a set of observations made in December 1994 with the UH AO system mounted on the CFH telescope. North is up and East is left. Titan's angular diameter is 0".7 arc-seconds. Note the bright patch near the equator/southern hemisphere. Its longitude corresponds well to that of the bright spot seen in the HST images of Smith et al.

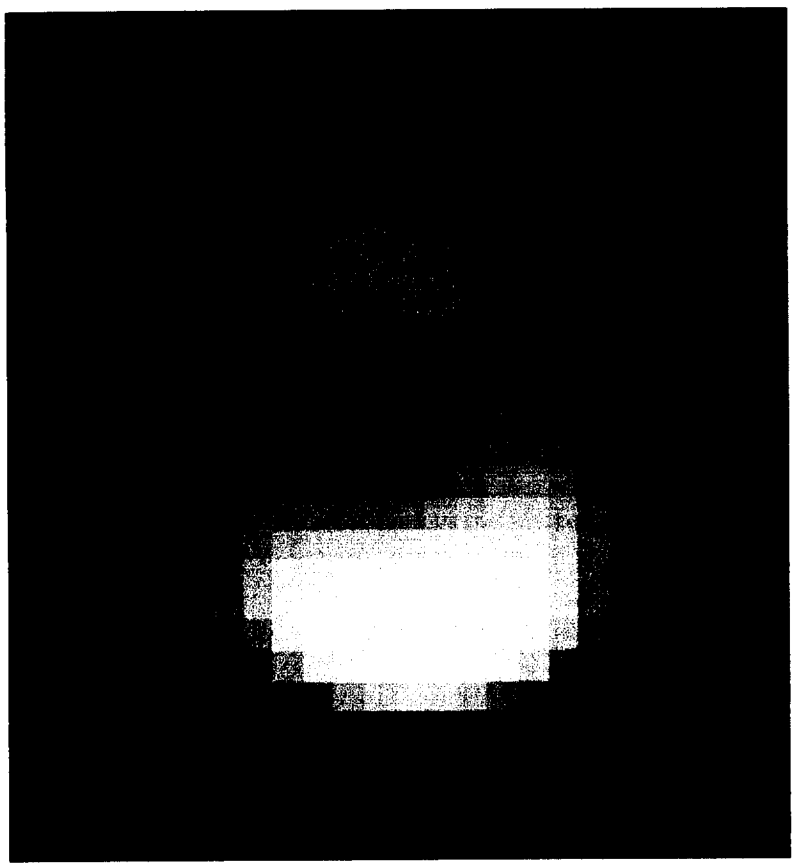

Fig. 4. Titan K-band image taken near greatest western elongation (LMC of 280°). This image is taken from a set of observations made in August 1995 with the UH AO system mounted on the CFH telescope. North is up and East is left. Titan's angular diameter is 0".7 arc-seconds. The dark spot near the equator is a feature seen on two consecutive nights with an approximately 7% decrease in flux from a profile fitted to the data with the spot masked out (this fit has not been subtracted here). There is a significant north-south hemispheric asymmetry in this image, reminiscent of the asymmetry seen by Voyager.

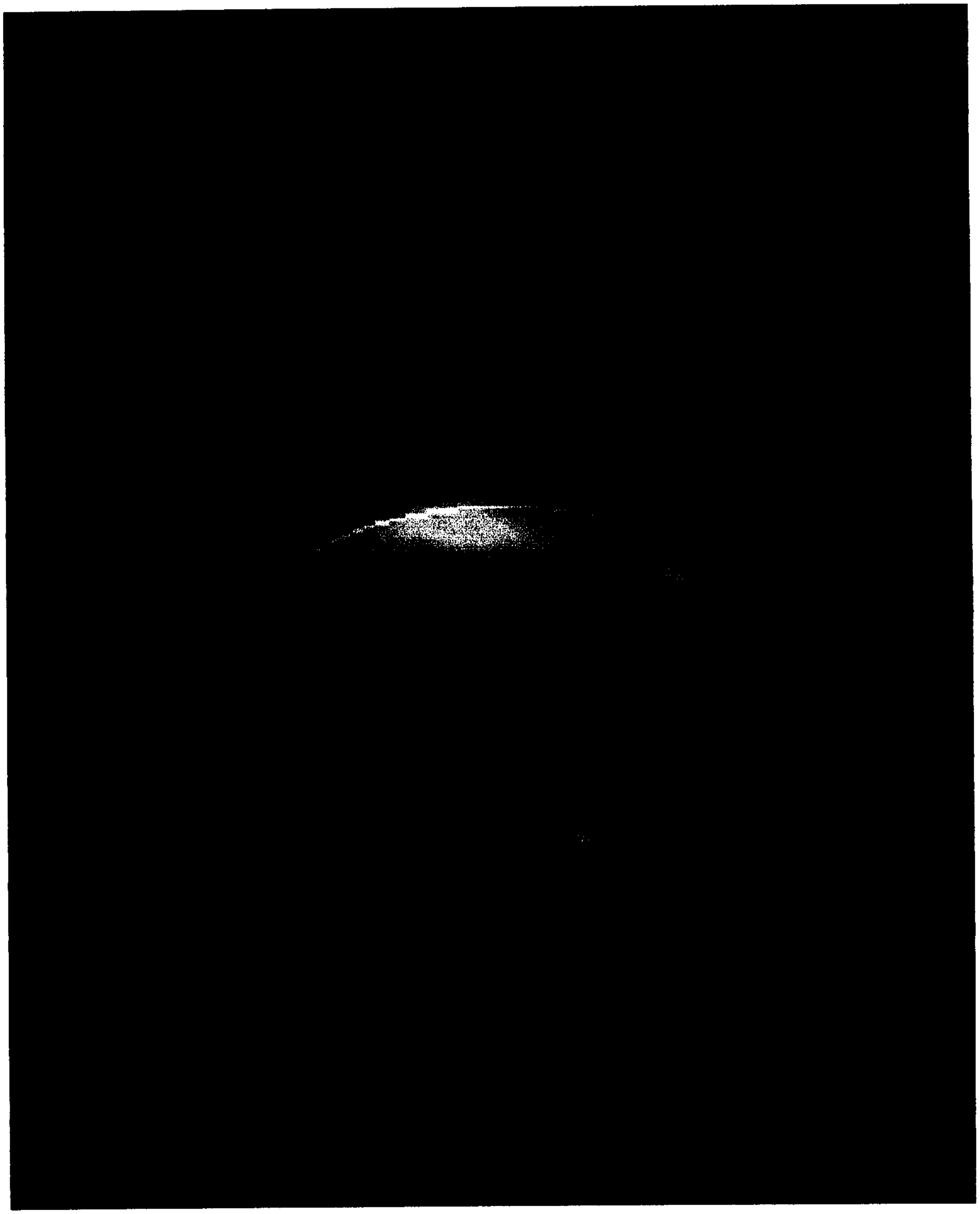

Fig. 5. Neptune K-band image obtained on August 12, 1995 at 10h 38m (UT) with the UH AO system mounted on the CFH telescope. North is up and East is left. Neptune's angular diameter is 2".4. Bright high contrast features are believed to be high altitude clouds. They confirm that low latitude (< 30°) cloud activity has shifted since Voyager from the south hemisphere to the north hemisphere, whereas higher latitude activity seems more permanent. Above Neptune, slightly on the right side, Proteus can be seen at the exact location predicted from Voyager data. This is the first ground-based detection of this dark satellite discovered by Voyager 2. Its K-magnitude is estimated to be 19.0 ± 0.03. The corresponding geometrical albedo is identical to that measured in the visible by Voyager.

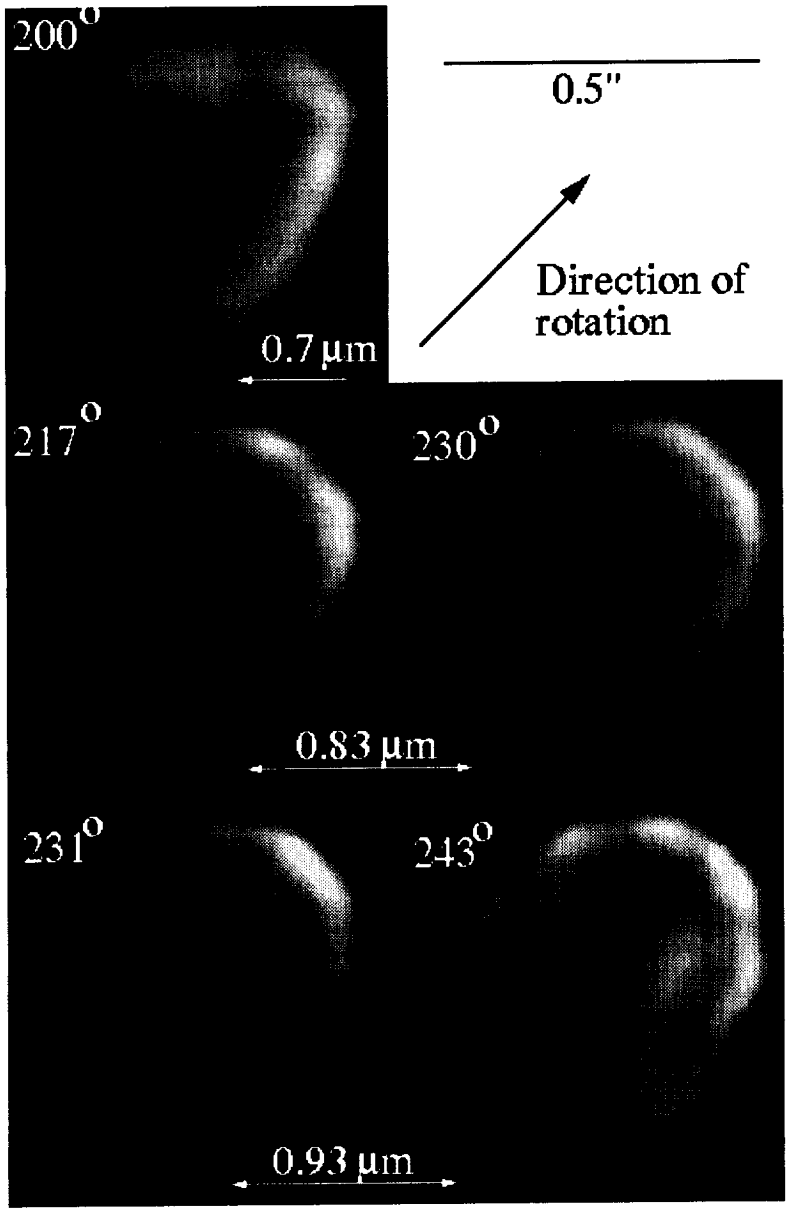

Fig. 6. Images of Vesta recorded with the Mt Wilson adaptive optics system on the 100" telescope. They were recorded on June 14, 1996, while Vesta was one month after the opposition time. Its mean angular diameter was then 0.55 arcsecond. Vesta was imaged through narrow band filters outside the pyroxene band (0.7 µm, top row) and inside the absorption band (0.83 µm, middle row - and 0.93 µm, bottom row). The corresponding central longitude is noted at the top left corner of each image. The direction of rotation of Vesta is indicated by the arrow in the top right corner. The axis of rotation is perpendicular to this direction. The total rotation angle between the first and last images shown here is 45 degrees. The rotation of the diverse albedo marks is visible as well as the relative brightness variation of these features while we go deeper in the pyroxene band , from 0.7 µm to 0.93 µm. These changes correspond to some local variation in the mineralogical composition of Vesta surface. The images recorded at 0.83 and 0.93 µm are more sensitive to pyroxene rich regions (darker) which correspond to relative "young" areas on the surface of Vesta (impact craters or lava flows) compared to the rest of the basaltic crust (older) rich in feldspar.